THE CHARACTERIZATION OF A LAYERED SAPROLITE/FRACTURED BEDROCK AQUIFER

David Radzieta

AUTHOR: EMCON Southeast, 1575 Northside Drive Ste. 435, Atlanta, Georgia 30318
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ABSTRACT

The hydrogeology of a piedmont saprolite/fractured rock aquifer has been defined through geological mapping, observation well boring logs, watershed analysis, and aquifer testing. The proper analysis of a weathered piedmont crystalline aquifer requires a multidisciplinary approach of geology, mechanics, and hydraulics. The geology is characterized to interpret the stress/strain history of the aquifer. The stress/strain history provides a basis to design an aquifer test. Analysis of the aquifer test requires an indepth understanding of the geological controls upon the aquifer and the hydraulics of fractured rocks. From the aquifer test analysis; the effective fracture radius (1900 feet), the bedrock anisotropic hydraulic conductivity (K_x = K_y = 66 ft/min and K_z = $6.5x10^{-4}$ ft/min), the radial zone of drawdown influence (approximately 2000 feet) and the long-term well yield (between 200 and 270 gpm) has been determined through this short, but carefully planned water-supply investigation.

INTRODUCTION

The Lawrenceville well field has been considered the most productive well field in the crystalline piedmont of Georgia (Herrick and LeGrand, 1949). Several wells in the field produce over 200 gallons per minute (gpm). The city of Lawrenceville used to operate 3 wells in the field until 1970 when surface water was developed. In recent years, water resources have become more expensive. In periods of drought, the city can be penalized for exceeding their water allocations. This water-supply investigation was conducted to determine the feasibility of reactivating some or all of the 3 former City of Lawrenceville wells. This paper discusses the hydrogeological aspects of the water-supply investigation, the methodology and logic behind the hydrogeological analysis, and the methods used to quantify and characterize hydraulic properties of a well from this field.

GEOLOGICAL MAPPING

The geology of the site and surrounding areas was researched and field mapped to design the aquifer test and determine the factors controlling groundwater flow in the aquifer. General geological maps were reviewed and a field reconnaissance was conducted to measure rock fabrics.

The principle rock types in the area include quartzites, amphibolites, gneisses, and schist. In the field some degree of interlayering is present but interlayering is most evident on regional geological maps of the area compiled by McConnell and Abrams (1986, Figure 1).

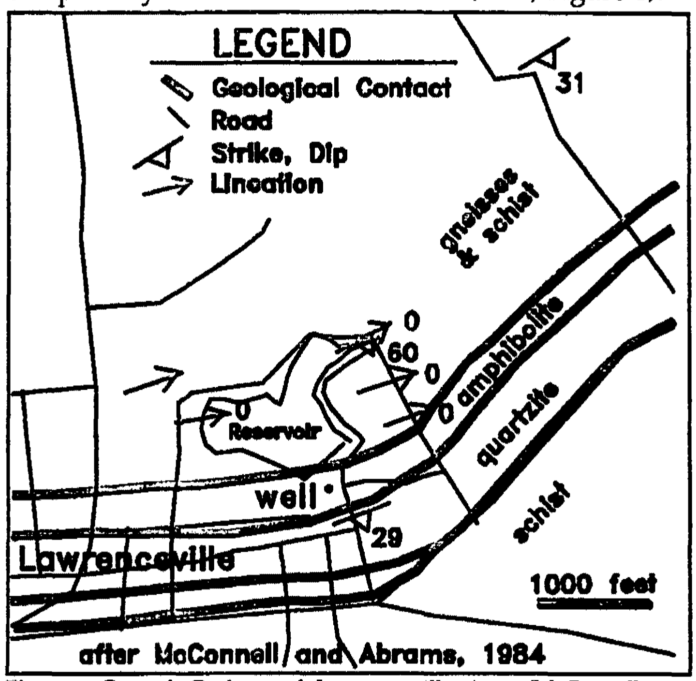

Figure 1 General Geology of Lawrenceville Area (McConnell and Abrams, 1986).

The interlayering and geological contacts between rock types can create a preferred avenue for groundwater transport. This anisotropy is a result of the different elastic and physical strengths of the varying mineral compositions within the rock. Two rocks with different mineral compositions react differently to applied stresses which often results in the two rock types separating and forming interlayer separations or interlayer discontinuities. Therefore, the observed direction of rock foliation is anticipated to be aligned with one of the principle directions of the hydraulic conductivity ellipsoid.

Rock foliations in the vicinity of the well were measured to determine the principle alignment of rock interlayers. Rock lineations measured in gneisses 1500 feet northwest of the test well are oriented approximately N75°E, 0° plunge. Schistose outcrops approximately 300 feet southeast of the test well strike approximately N65°E and dip 30°E. Attitudes measured in amphibolitic rock outcrops approximately 1200 feet northeast of the test well have lineations oriented from N60°E to N65°E, 0° plunge. These attitudes (displayed on Figure 1) are similar to the general nature of contacts in the area presented by McConnell and Abrams (1986).

Fracture and joint discontinuities were observed in the field. Rock discontinuities, including interlayer separations, can create avenues of preferred groundwater transport in the subsurface. Irregular orthogonal jointing systems were observed in amphibolitic rock outcrops northeast of the test well. These orthogonal systems were weakly developed and often impossible to discern. One set of discontinuities would orient along the lineation and another set roughly perpendicular to the foliation.

Joints are the result of tensional stress or least compressive deviatoric stress in the bedrock. The principle compressive stress axis is believed to be oriented normal to the rock layering for two reasons: 1. continual spreading of the atlantic mid oceanic ridge and 2) the residual elastic rebound of metamorphic minerals trying to recover from tectonic mountain building forces. Joints align normal to this compressive stress direction or normal to the rock lineation or foliation. Therefore, the direction normal to the rock fabric is anticipated to be a principle axis of hydraulic conductivity.

OBSERVATION WELLS

Four observation wells were drilled in the vicinity of the test well. Two deep wells, OW1 and OW2, were drilled to depths that intersected significant fractures. These wells were drilled 212 feet and 160 feet deep, respectively, and located equidistant from the test well; one well located along the principle geologic strike and another well located perpendicular to the geologic strike. The observation well spacing was approximately 200 feet for these two deep wells. Two additional wells, P1 and P2, were drilled approximately 20 feet deep to the top of competent rock. These two shallow wells or piezometers were also located 100 feet equidistant from the test well with similar orientations as the deeper observation wells.

Observation well 1 produced approximately 150 gpm during drilling after intersecting a fracture at 212 feet in depth. This well was drilled through predominantly biotite hornblende gneisses and amphibolites. The water-bearing fracture appears to be the result of a geological contact since quartz fragments were abundant at that depth. Observation well 2 was drilled approximately 160 feet in depth where it intersected a water-bearing fracture that roughly produced 100 gpm during drilling. This well was also drilled through biotite hornblende gneisses and amphibolites with a five to ten foot thick quartzite interlayer at approximately 50 feet in depth below ground surface. The water producing zone at 160 feet appears to be related to a lithology change from biotite hornblende gneisses and amphibolite to an underlying quartzite layer. The shallow wells were drilled through silty sand saprolite where two foot long hand slotted well screens were installed at the top of competent bedrock.

The deeper observation wells would record any head loss (drawdown along anticipated horizontal hydraulic conductivity axes. The shallow observation wells measured the vertical component of head loss and hopefully would allow for a determination of the vertical hydraulic conductivity and a true representation of the hydraulic conductivity ellipsoid for this test. Additionally, the shallow wells were to determine the effects withdrawals would have upon nearby surface water features such as a reservoir or a stream located nearby.

WATERSHED ANALYSIS

The watershed above the test well was delineated. The area of the watershed is approximately 1 square mile or 2.8×10^7 ft^2 (Figure 2). Assuming 60 inches/year (5 ft/year) precipitation and approximately 15% infiltration after accounting for runoff and evapotranspiration, approximately 2.1×10^7 ft^3/yr are available for aquifer recharge in the watershed. This amounts to approximately 40 ft^3/minute or 310 gpm in the watershed. This can be considered a rough maximum amount of available water for a well field within this watershed basin. However, discharges of this amount would certainly have detrimental effects upon the watershed, therefore approximately 200 to 250 gpm is considered the maximum sustainable discharge rate.

AQUIFER TEST -- STEP RECOVERY

An aquifer step recovery test was performed to estimate the well efficiency and determine a safe withdrawal rate for an extended aquifer test. A step recovery test attempts to shorten the time required to obtain stabilized water levels at each step by rapidly

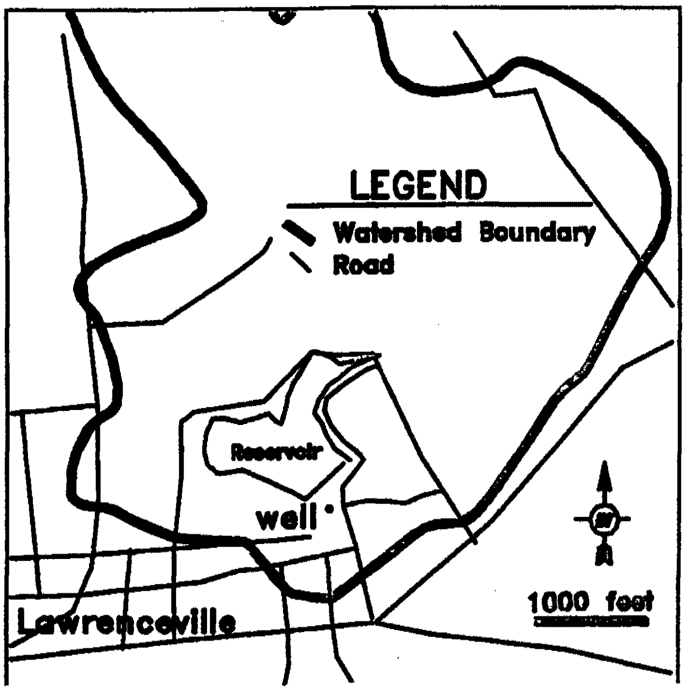

Figure 2 Watershed Area Above Test Well.

depleting the well and nearby aquifer storage. Once the drawdown is lowered, each recovery step requires a shorter time duration to reach equilibrium. Results of the step recovery test are presented in Figure 3. The small amount of recovery evident after the pump shut-off indicates that the aquifer is finite in dimension (has definite limits of overall storage similar to a bathtub).

AQUIFER TEST -- INTERFERENCE TEST

The interference test was performed over a twenty-eight hour period during which records were maintained for the rate of well discharge, the drawdown in the deep observation wells, and drawdown in the shallow wells.

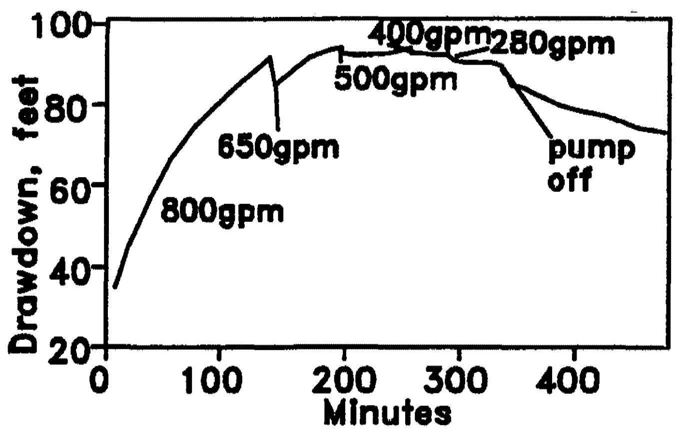

Figure 3 Step Recovery Test.

The discharge rate varied from 265 to 275 gpm over the extent of the test (270 gpm is considered average). This discharge rate was selected to ensure that the drawdown did not exceed approximately 33% of the saturated aquifer thickness. Drawdown in the discharge well and the two deeper observation wells is almost identical (Figure 4).

Drawdown in the shallow wells was minimal, but distinct when plotted on the logarithmic scale (Figure 4). This raw data implies extensive horizontal fracture flow that extends several hundred feet to perhaps several thousand feet from the well in all directions. The lack of significant drawdown in the shallow wells indicates that groundwater flow in the vertical direction is limited. The resulting three dimensional hydraulic conductivity ellipsoid can be considered an oblate spheroid (squashed pancake) based upon the preliminary data -- water flows horizontally with ease but vertical flow is limited.

In order to determine the effective drawdown radius of the well, several sophisticated analytical solutions exist that are applicable for different types of aquifers. Many of these solutions employ the method of curve matching. This solution requires that the drawdown curve for the

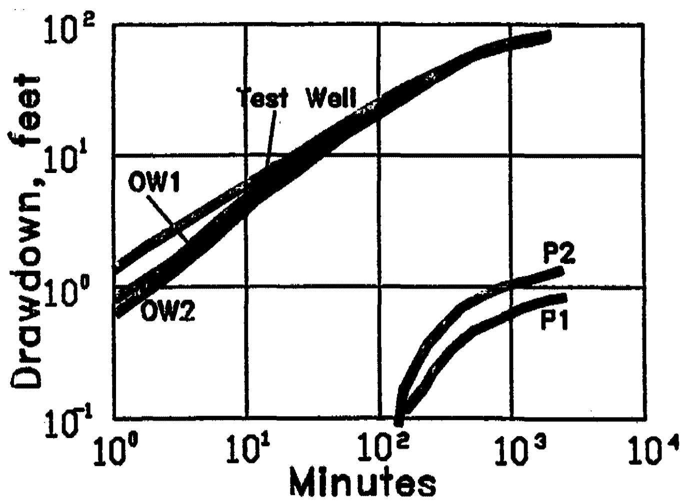

Figure 4 Aquifer Test Drawdowns.

observation or discharge well be matched to a type curve for an analytical solution. Figure 5 shows the type curves of Karasaki (1986) that provided the most reasonable match and satisfy the geometry of the fractured aquifer. Type curves of Boulton and Streltsova (1977, 1978), Theis or others did not provide as reasonable a match.

The Karasaki analytical method assumes a linear radial flow regime with double porosity characteristics. Flow in the inner region is assumed to occur in fractures and obey the cubic law of flow for fractures. The outer region, where the effective fractures end, is dominated by radial flow where the hydraulic conductivity is related to

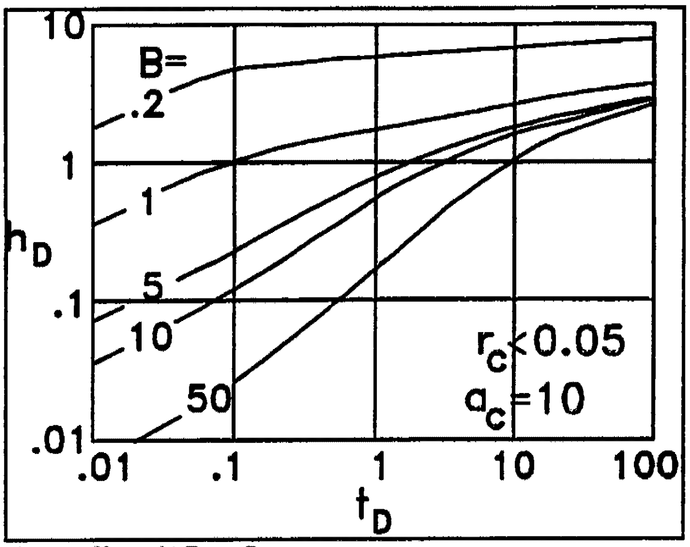

Figure 5 Karasaki Type Curves.

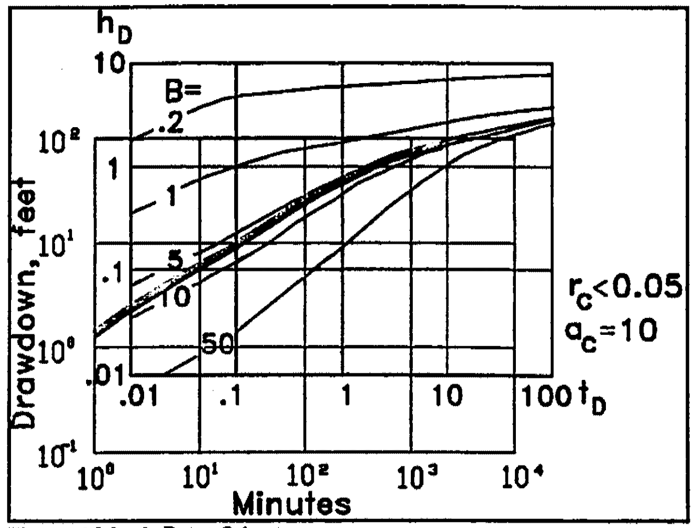

Figure 6 Match Point Selection.

&the square of the particle sizes that comprise the aquifer – granular porous media matrix flow. When the permeability of the fractures is several orders of magnitude greater than the matrix, early drawdown data is similar to that expected with nearby impermeable boundaries (i.e. the finite storage capability as determined from the step recovery test). Also flow in the inner region gives a characteristic half slope when plotted on logarithmic paper. The following dimensionless equations are used to derive an analytical solution for this system once a type curve match has been selected [for a derivation of these equations see Karasaki, 1986].

Eq. 1 $$h_D = \frac{2\pi K_2 H(\Delta h)}{Q}$$

Eq. 2 $$t_D = \frac{a_2 t}{r_f^2}$$

Eq. 3 $$10 = a_c = \frac{a_1}{a_2} = \frac{K_1 S_{S1}}{K_2 S_{S2}}$$

Eq. 4 $$B = 7.5 = \frac{nbK_1}{2\pi r_f K_2}$$

Match points (Figure 6) are selected as follows: t = 2.8 min, t_D = 0.01, h = 0.65 ft, h_D = 0.01, a_c = 10, B = 7.5, Q = 36 ft/min, H = 250 ft, and r_w = 0.42 ft.

Inserting these values into Equation 1, k_2, or the matrix material (outer flow region) is 3.5×10^{-4} ft/min. This is not the k of the saprolite, although the number is what is expected, this is actually the apparent k beyond where linear flow is occurring. We now have 3 remaining equations and four unknowns: k_1, r_f, S_{s1}, and S_{s2} (since a = k/S_s).

We can study the inter-relationships of k_1, S_{s1}, and S_{s2} by looking at acceptable values and narrowing the possible ranges for a final solution. From Equation 3, if $S_{s1} = 10^{-9}$ and $S_{s2} = 10^{-5}$, then k_1 = approximately 10^1. These specific storage values may be approximately equal to the expected values for a fissured crystalline rock and saprolite aquifer, respectively.

We can also look at k in terms of drawdown by trying to obtain an approximate value using a different method. Throughout the aquifer test, the drawdown in the discharge well remains approximately 1 foot greater than the drawdown in the two deep observation wells. This implies a constant head gradient or pseudo steady-state flow condition exist. The Thiem equation has often been used to derive steady-state k values for granular media. Using the Thiem equation ($k=[Q/(piH^2)]\ln(r_2/r_1)$) where dh = 1 ft., Q = 36 ft^3/min, r_2 = 200 ft, and r_1 = 1 ft, the approximate k_1 is 61 ft/min.

For a fractured media the cubic law must be presented in radial coordinates for flow to a well. Gale (1975) presented an equation (Equation 5) that he used to correlate video camera boring logs to fracture apertures. This equation has the desired radial coordinate system necessary to determine the effective fracture aperture.

Eq. 5 $$b = \sqrt[3]{[-[\frac{12Q\mu}{2\rho_w g\pi}](\ln r_b - \ln r_w)] + \Delta H}$$

Using Equation 5 with the values from the aquifer test, the effective fracture aperture (b) is 0.48 ft. Inserting this b value into Snow's formula ($k = pgb^2/12u$) for the hydraulic conductivity of a fracture, k_1 = 72 ft/min. This is surprisingly close to the value obtained using the Thiem equation. Therefore this value is averaged with the Thiem k value and inserted into Equation 4. From Equation 4, and assuming that the number of fractures is effectively represented by a single fracture through the sum of the apertures thus obeying Snow's law, the effective fracture radius is 1900 feet. This radius is expected to be directly influenced by withdrawal from the test well. An additional amount of influence is expected to occur in the outer zone where transport mimics radial flow.

CONCLUSIONS

Short term well yields of 270 are considered optimum for the well, however the aquifer cannot maintain this discharge rate since it is of finite dimensions and has a finite recharge capacity. Long-term aquifer yields of 200 to 250 gpm are considered reasonable sustainable discharges. The optimum well yield is not limited by borehole skin. The effective fracture radius is 1900 feet and therefore the effected zone of discharge influence is anticipated to be approximately 100 to 200 feet beyond this range. The saprolite and microfracture storage in the inner radius will be directly influenced by continual withdrawals; the influence this will have upon the nearby reservoir is uncertain. Although inexact, these values for k_1 and r_f appear reasonable when compared to aquifer test drawdowns and k values obtained using different methods.

Numerous techniques are available for the characterization and quantification of fractured aquifers of various geometries. An understanding of the geological controls is necessary for designing the aquifer test. The drawdown data has to be plotted log-log fashion to correctly identify skin effects, linear flow behavior, constant head boundary behavior, unconfined flow behavior, or granular media flow behavior, etc. The field data has to be interpreted and compared with the dozens of methods available for analyzing fractured rock aquifers.

Additional work is possible to fully integrate the drawdowns observed within the shallow piezometers. Neuman, Hantush, Witherspoon and others have devised numerous analytical methods that may be applicable for analyzing drawdown curves observed in the shallow wells. This may be conducted at a later date as part of a Master of Science Thesis in Hydrogeology by the author.

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NOMENCLATURE

p = water density
g = gravitational acceleration constant
a = hydraulic diffusivity
a_c = ratio of fracture hydraulic diffusivity to outer region hydraulic diffusivity
t = match point aquifer test time
t_D = dimensionless time
h = match point aquifer test drawdown
h_D = dimensionless drawdown
n = number of fractures
n = effective porosity
H = aquifer thickness
k_1 = inner zone (fracture) hydraulic conductivity
k_2 = outer zone (matrix) hydraulic conductivity
B = hydraulic conductivity / geometry partitioning variable inner to outer region
r_f = effective fracture radius
r_w = radius of well
S_{s2} = specific storage outer region
Q = discharge rate